

SPACECRAFT HYBRID (MIXED-ACTUATOR) ATTITUDE CONTROL EXPERIENCES ON NASA SCIENCE MISSIONS

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ABSTRACT

There is a heightened interest within NASA for the design, development, and flight implementation of mixed-actuator hybrid attitude control systems for science spacecraft that have less than three functional reaction wheel actuators. This interest is driven by a number of recent reaction wheel failures on aging, but what could be still scientifically productive, NASA spacecraft if a successful hybrid attitude control mode can be implemented. Over the years, hybrid (mixed-actuator) control has been employed for contingency attitude control purposes on several NASA science mission spacecraft. This paper provides a historical perspective of NASA's previous engineering work on spacecraft mixed-actuator hybrid control approaches. An update of the current situation will also be provided emphasizing why NASA is now so interested in hybrid control. The results of the NASA Spacecraft Hybrid Attitude Control Workshop, held in April of 2013, will be highlighted. In particular, the lessons learned captured from that workshop will be shared in this paper. An update on the most recent experiences with hybrid control on the Kepler spacecraft will also be provided. This paper will close with some future considerations for hybrid spacecraft control.

I. INTRODUCTION

Currently NASA has 57 science spacecraft in extended mission operations. Because NASA has many aging but still scientifically productive spacecraft, coupled with a number of recent reaction wheel (RW) failures, a heightened interest has been spurred within the Agency for the design, development, and flight implementation of mixed-actuator hybrid systems. These hybrid systems serve to maintain three-axis attitude control and extend science productivity of the spacecraft that suffer RW in-flight failures. Examples of these include Kepler, Mars Odyssey, Cassini, and Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED). Hybrid control is envisioned as a general means to ensure continued longevity of NASA's scientific spacecraft fleet well past their prime mission lifetimes and into productive extended science mission operations.

In late 2012, NASA's Science Mission Directorate (SMD) requested the support of the NASA Engineering and Safety Center (NESC) Guidance, Navigation, and Control (GN&C) Technical Discipline Team (TDT) to plan and conduct a NASA-wide workshop on lessons learned and current developments in "hybrid" (mixed-actuator) spacecraft attitude control mode design, test, and operations. A hybrid attitude control mode is a contingency means for controlling a spacecraft that has lost the use of one or more of its RW complements such that there are less than three functional operating RWs remaining.

During the period leading up to the workshop there were a number of NASA missions either actively working on designing and implementing hybrid attitude control or at least considering the feasibility of candidate hybrid control techniques. In particular, the Dawn mission, the Mars Odyssey mission, and the Kepler mission were working on or considering the use of such a hybrid contingency attitude control mode for their respective inflight science spacecraft. There are also several other missions that may be facing RW failures as they age and could potentially benefit from contingency hybrid control.

In the following sections of this paper, summary-level highlights from the NASA Spacecraft Hybrid Attitude Control Workshop will be provided. This will primarily consist of a set of brief historical summaries of NASA's work on past spacecraft mixed-actuator hybrid attitude control approaches. This paper will also document the key lessons learned captured at the workshop. A number of initiatives were spawned following the April 2013 workshop. Some specific examples of current hybrid control research, design, development, and test will be described. Technical areas for future considerations will also be identified.

II. NASA SPACECRAFT HYBRID ATTITUDE CONTROL WORKSHOP SUMMARY

The primary motivation behind holding the workshop was to identify and capture lessons learned and best engineering practices emerging from the several NASA missions that had in the recent past analyzed, designed, implemented, and operated in a hybrid attitude control mode.

Therefore, in April of 2013, the NASA Technical Fellow for GN&C (assisted by members of his NESC GN&C TDT) conducted what is believed to be the first ever NASA-wide workshop-type meeting focused on both the Agency's historical experience with contingency spacecraft attitude control using only two reaction-wheel (2-RW) units and some current relevant activities. The 2-day workshop also focused on the technical feasibility of 2-RW contingency attitude control for three particular NASA science spacecraft: namely Dawn, Mars Odyssey, and Kepler. In this context, 2-RW contingency attitude control refers to hybrid mixed-actuator attitude control modes of operation in which reaction control thrusters and/or magnetic torque actuators are combined with the two remaining functional RWs on a given spacecraft to provide the requisite set of required attitude control torques. In some cases, the local environmental disturbance torques, such as those arising from gravity gradient, aerodynamic or solar radiation pressure disturbance, can be harnessed to work in tandem with the two remaining functional RWs to obtain three-axis attitude control authority.

III. HYBRID ATTITUDE CONTROL WORKSHOP GOALS

NASA wants to position itself to be as knowledgeable and as prepared as possible for contingency attitude control operations with only two (or possibly one) RWs on missions such as Dawn, Mars Odyssey, and Kepler. The specific SMD goal of the workshop was to help inform and prepare the Kepler, Dawn, and Mars Odyssey attitude control system (ACS) teams to understand better the technical challenges, risks, and benefits of potential 2-RW hybrid attitude control mode operations on their spacecraft. It was a mutual goal of the SMD and NESC to have the engineering knowledge in this particular spacecraft GN&C area to be shared amongst the subject matter experts from across the NASA Centers and our industry and research partners. The identification of specific engineering areas and/or technology ideas for follow-on work in this area of hybrid control that would mitigate design and development risk and on-board implementation risk for future NASA space science missions was also an NESC goal for this workshop.

A. SPECIFIC HYBRID ATTITUDE CONTROL WORKSHOP OBJECTIVES

The specific objectives of the NASA Spacecraft Hybrid Attitude Control Workshop were to:

- 1) Review recent inflight RW failures.
- 2) Review contingency hybrid (2-RW) attitude control past experience, to include re-design analysis and implementation details (e.g., specific attitude control law modifications).
- 3) Capture key lessons learned from historical experiences with hybrid attitude control.
- 4) Discuss the constraints on and limiting factors for hybrid (2-RW) attitude control and review what is technically feasible with hybrid (2-RW) attitude control.
- 5) Discuss the risks of implementing hybrid (2-RW) contingency attitude control.
- 6) Discuss the current state of the Kepler, Dawn, and Mars Odyssey spacecraft RW attitude control capabilities and consider the following questions:
Is there an imminent risk of another on-board RW failure?
Are there vehicle-unique aspects to impending hybrid control on any of these spacecraft?
- 7) Assess the potential for implementing contingency hybrid (2-RW) attitude control on Kepler, Dawn, and Mars Odyssey by evaluating the technical risks/benefits including a consideration of the degree of implementation difficulty.

The workshop was purposely conducted in a collegial manner with an open sharing of hybrid control ideas and methods of operating scientific spacecraft with a reduced complement of RWs. Twenty-eight attitude control subject matter experts from a combination of commercial industry (both large primes and small businesses), academia, non-profit labs, government labs, and NASA Centers participated in the workshop. Fig. 1 is a group photograph of the workshop participants.



Fig. 1: Group Photograph of NASA Spacecraft Hybrid Attitude Control Workshop Participants

By definition, none of the briefings contained any of their organizations' proprietary, confidential, or trade secret information. The Orbital Sciences Corporation (OSC) and Johns Hopkins University (JHU) Applied Physics Lab (APL) each provided some hybrid control historical perspective by describing their successful contingency operations for the Far Ultraviolet Spectroscopic Explorer (FUSE) and TIMED spacecraft, respectively. Both OSC (FUSE) and APL (TIMED) reported on how, through a series of innovative and clever engineering approaches, they each were successful in enabling the continuation of their science missions for many years beyond their required design life despite having experienced multiple inflight RW failures. OSC, Lockheed Martin Company (LMC), and NASA described their work on hybrid control techniques for Dawn and Mars Odyssey. Engineers from the NASA Jet Propulsion Laboratory (JPL) described their hybrid control work on Cassini and presented the results of a preliminary hybrid control feasibility study for Kepler. The Ball representative to the workshop provided an overview of the Kepler ACS and described the history of RW anomalies on Kepler. In the following sub-sections of this paper, a brief summary will be provided on each of the above topic areas covered during the workshop.

IV. FUSE HYBRID CONTROL WORKSHOP REPORT

OSC presented a summary-level presentation on the work Orbital and JHU APL engineers performed in 2004 to design and implement a hybrid ACS for the FUSE satellite. The FUSE spacecraft (see Fig. 2) was launched into orbit in June 1999 and began a 3-year prime mission to collect high-resolution spectra in the far ultraviolet wavelength. FUSE flew in a circular low Earth orbit (LEO), approximately 725 km in altitude, with an inclination of 25 degrees and with an orbital period of slightly less than 100 minutes. Like most zero-momentum, three-axis stabilized spacecraft FUSE employed a RW-based ACS. The spacecraft was equipped with a set of four RWs. In November 2001, the yaw RW on FUSE suffered dramatically increased drag and ceased spinning, but science operations continued with the redundant skew RW controlling yaw in a three-wheel mode. In December 2001, the pitch RW also suffered a similar failure, leaving the spacecraft with only two axes of control. Therefore, 2.5 years after launch, mechanical failures of two out of four RWs reduced the satellite to two-axis control, halting science observations.

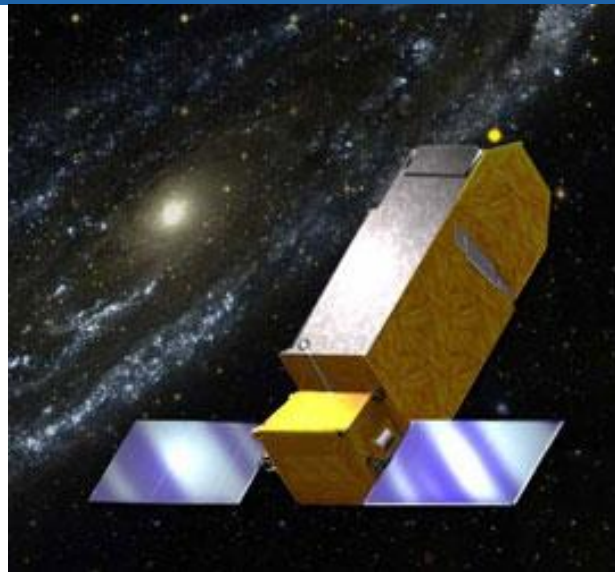


Fig. 2: FUSE Spacecraft

The FUSE spacecraft's zero-momentum, three-axis stabilized ACS was reconfigured to use the remaining two functional RWs to stabilize the spacecraft in pitch and roll, but science operations were not possible due to an uncontrolled tumble in yaw. Efforts by the FUSE flight operations team to re-start both the yaw and pitch RWs resulted in no detectable motion. After the yaw wheel failure in November 2001, while still operating in three-wheel mode, preliminary investigations began into the feasibility of using the magnetic torquer bars (MTBs) to generate attitude control torque in a mixed-actuator or 'hybrid' actuator configuration. The interaction of MTBs with the Earth's geomagnetic field has been a technique used since the 1960s to provide attitude control for momentum-bias spacecraft [1]. It was not immediately clear that employing the MTBs, together with the two remaining reaction wheels, would be compatible with the existing ACS design and three-axis control requirements of FUSE. MTBs have also been suggested as a method of control for the class of spacecraft whose design provides inherent gravity gradient stabilization, but the science demands required that the FUSE spacecraft observe celestial targets all over the sky and hold attitudes that did not minimize gravity gradient torques. At any rate, purely magnetic pointing control up until this time had only been applied to missions where the tolerances for attitude control were at the relatively coarse 1-degree or more pointing level.

Since torque can never be generated about the instantaneous geomagnetic field vector, any mission that uses magnetic control torques must have additional actuators, or accept attitude disturbances about a vector that is moving relative to inertial space. In the case of FUSE, these additional actuators were the two remaining functional RWs. Initial calculations showed that the MTBs could be commanded with sufficiently high bandwidth for fine pointing control within the science requirements, and that they could produce enough torque to cancel external disturbances, but only at some spacecraft orientations. The 25-degree inclination of the FUSE orbital plane placed geometrical constraints on the use of magnetic control. The direction of the Earth's magnetic dipole is almost constant in the Earth frame at 11.5 degrees from its spin axis. In a low-inclination orbit, a spacecraft will not see as much variation in the local magnetic field direction as it would in a higher inclination orbit. In a polar orbit, there will be a lot of inertial turning around of the field over an orbit. In a low-inclination Earth orbit the magnetic torqueing takes longer because it is less efficient.

After the second permanent RW failure in December of 2001, simultaneous efforts began to upgrade the ACS software to accomplish magnetic control and to develop ground-based models useful for predicting stable spacecraft orientations. It was described how these RW failures prompted modification of the FUSE ACS flight software to restore three-axis control using a hybrid configuration of existing magnetic and RW actuators. Pointing accuracy and stability were once again accomplished at the sub-arc second level, close to the pre-wheel failure performance and momentum control was still automatically handled. The range of stable attitudes at any given time was limited, but a new ground-based software model was developed which directed the spacecraft observation planning process such that observations and maneuvers stay within the limits of the actuators.

In December of 2004, the roll wheel permanently failed, leaving just the skew wheel and magnetic torque rods for control. FUSE again was able to get back into science operations, but at a reduced pointing accuracy of a

couple arc-seconds. Additionally, the momentum unloading had to be performed via science target selection and swapping, wherein one target would load momentum and the other would unload momentum.

In July 2007, FUSE's final working RW, the skew wheel, failed and efforts to restart it were unsuccessful. An announcement was made in September 2007 that because the fine control needed to perform its mission had been lost, the FUSE mission would be terminated.

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References 2 and 3 contain the details of the FUSE hybrid control (both 2-RW and 1-RW) design and development process.

In Summary, thanks to the implementation of a hybrid control ACS, FUSE was able to meet its primary science mission of 3 years of science operations, in addition to continued productive science operations to 8 years, instead of falling short of mission objectives with the second RW failure at 2.5 years.

V. TIMED SPACECRAFT HYBRID CONTROL WORKSHOP REPORT

As part of NASA's Solar Connections Program, the TIMED mission has the primary objective of investigating and understanding the energetics and dynamics of the mesosphere and lower thermosphere/ionosphere region. Launched on 7 December 2001, the TIMED spacecraft was built, and is operated, for NASA by the JHU APL. TIMED is a 600-kilogram spacecraft (see Fig. 3) carrying four primary instrument payloads. Launched into a 625-kilometer circular orbit with an inclination of 74.1 degrees, the original mission lifetime for TIMED was 2 years and has since been granted multiple mission extensions.

The RW-1 unit on the TIMED spacecraft exhibited an increase in running friction on 15 February 2007 and it was autonomously removed from the attitude control loop [4]. Several attempts to restart RW-1 were unsuccessful. This failure of RW-1 appeared to make the remaining wheels on TIMED suspect and mission managers initiated steps to be prepared for any subsequent wheel failure. It was decided to re-design the baseline attitude controller to implement a 2-RW/magnetic torque-rod hybrid control approach similar as to what was done on the FUSE mission. The team's objective was to develop and test the attitude control flight software modifications (i.e., 'patches') prior to a subsequent wheel failure.

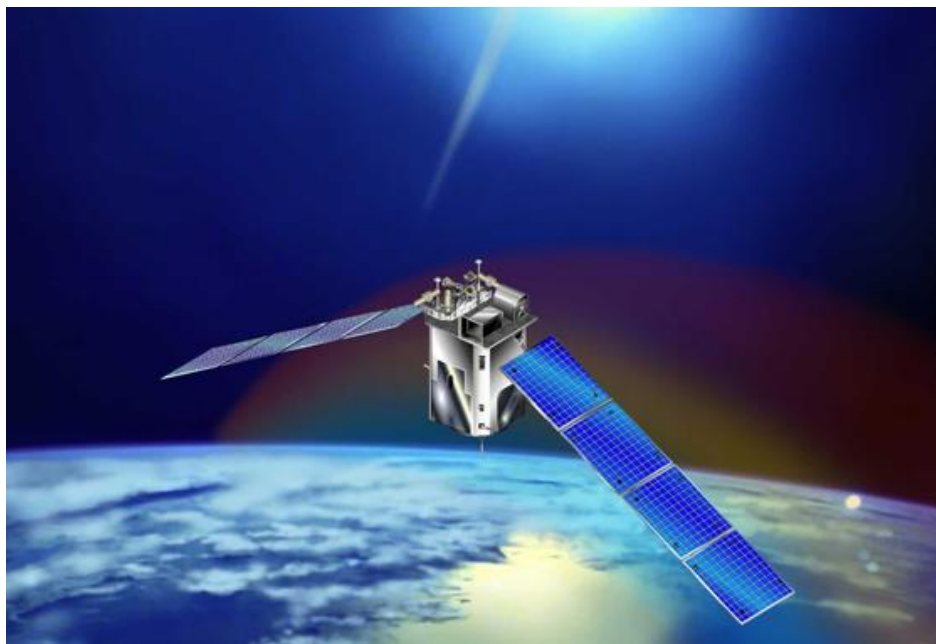


Fig. 3: TIMED Spacecraft

However, a fundamental difference was that while the FUSE spacecraft was inertially pointed for its science observations, the TIMED spacecraft is nominally a nadir-pointing platform. Yet another key difference was that while there is a capability to energize the magnetic torque rods proportionally on FUSE, the torque rods on TIMED were operated in a basic on/off manner. Since the rods are operated in an 'on' (fixed full-dipole command) and 'off' (zero-dipole command) way, the capability for 'fine' continuous proportional attitude control was reduced. The TIMED spacecraft hybrid controller was designed to "fire" the torque rod actuators in an on/off manner using phase plane logic, in a way very similar to how reaction control system (RCS) thrusters are typically used. The significant difference being that the TIMED magnetic torque rods, unlike RCS thrusters, only 'consumed' electrical current and not propellant. This is one example, however, of where there is a conceptual similarity between deep space mission hybrid control applications using modulated thrusters and LEO mission hybrid control using modulated magnetic torqueing.

As described in detail in Reference 5, some of the key findings of and/or design challenges to the JHU APL team working the TIMED hybrid control problem were among the following:

- Any two RWs provided control torque in a plane only. Therefore, the use of a Wheel/Rod Control Pseudo Frame would be a good basic first step in designing a new hybrid controller for TIMED.
- There was limited wheel control authority. In particular, the torque available on the spacecraft's x-axis was relatively small. There was a maximum control torque of ~13 mN-m on the x-axis as compared to ~59 mN-m on the y/z axes.
- Limited magnetic torque-rod output direction and magnitude causing under/over shoot or torque in undesired direction.
- There was only limited magnetic torque-rod control authority. Furthermore, the magnetic torque-rod authority depended on the *in-situ* magnetic field and spacecraft orientation. Torque rod output varied during an orbit (even crossing zero or remaining near zero) and changed from orbit to orbit.
- The TIMED RW configuration yielded very little x-axis body torque in two of the potential 2-RW configurations, so the magnetic torque rods would be called upon to primarily control the x-axis. It was further noted that another potential wheel configuration provided very little z-axis body torque.
- Only very limited control authority on the spacecraft's x-axis was available when the torques from both the y-axis and z-axis torque rods are near zero.
- Significant changes to the existing TIMED spacecraft operations philosophy were required; for example, due to poor attitude slew capability using only two wheels, the vehicle would always remain in nadir-pointing attitude, and the sun-pointing attitude was eliminated.
- The autonomous switch from 3-wheel nominal control to contingency 2-RW hybrid control was complicated due to the different autonomy (i.e., fault protection) rule sets involved. It was decided that the actual switch between the two control algorithms would be done automatically on-board through monitoring of the wheel health flag.
- The flight processor that hosts the attitude control flight software, the spacecraft's Attitude Interface Unit (AIU), had virtually no code space remaining with which to implement the new 2-RW hybrid control algorithm, so hosting the new 2-RW hybrid control algorithm in the AIU was precluded. An approach to change as little as possible inside the AIU was thus adopted.
- There were undesired torques acting on the spacecraft's x-axis: both precessional torque from wheel momentum due to vehicle's nominal orbital rotation about the y-axis and a torque from the vehicle's residual magnetic dipole.

Summary: To this date, the 2-RW reaction mode has not been needed to be implemented.

VI. CASSINI HYBRID CONTROL WORKSHOP REPORT

The JPL workshop presenter addressed the engineering performed by that organization on hybrid control for the Cassini spacecraft (see Fig. 4). Cassini was launched on 15 October 1997 and after an interplanetary cruise that lasted almost 7 years, it entered orbit around Saturn in June of 2004. After completion of its Saturn Orbit Insertion maneuver, Cassini began a complicated set of orbits about Saturn, designed to optimize science collection over not only Saturn itself, but also its icy satellites and moons. As with other spacecraft discussed at the workshop, the Cassini spacecraft has certainly demonstrated its longevity. It collected science data throughout its 4-year prime mission (2004–2008) and has since then been approved for an extended mission through 2017. In addition, like the other spacecraft addressed at the workshop, Cassini carries a set of four RWs, three of which are fixed orientation wheels and the fourth being a so-called "backup" RW (i.e., RW-4) that is mounted on top of an articulating platform. If necessary, this platform could be articulated to orient the backup

RW into co-alignment with the degraded wheel. RW-3 exhibited signs of bearing cage instability in the 2001–2002 time frame [6]. Consequently, the mission managers decided to articulate Cassini's RW-4 on its platform to align it with RW-3. Starting in July of 2003, Cassini was controlled using RW-1, RW-2, and RW-4. The Cassini flight operations team has worked to manage carefully the accumulation of the wheel revolutions. However, starting from their first use in 2000 to the present, RW-1 and RW-2 accumulated well over 3 billion revolutions each and there are some indications of increased drag torques of those wheels' bearings observed in telemetry. Reference 6 also describes some guidelines levied on Cassini science observations to extend RW life.

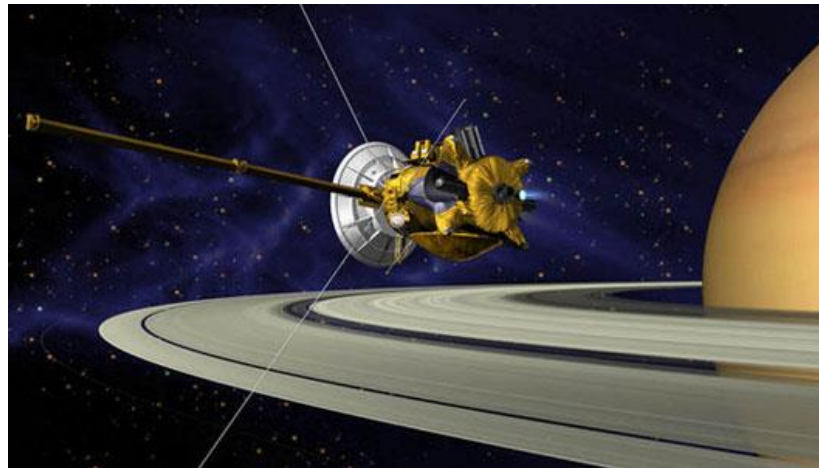


Fig. 4: Cassini Spacecraft

Given this situation, the Cassini mission managers proactively prepare for future RW degradations or outright wheel failures. Specifically, a study was initiated to investigate the feasibility of controlling Cassini using the two remaining functional RWs (i.e., RW-2 and RW-4) and four thrusters to meet the science pointing requirements for two different key science operational modes.

The two remaining RWs will not be able to provide precise and stable three-axis control of the spacecraft. In this study, the performance (e.g., the pointing control error, pointing stability, hydrazine propellant consumption rates, etc.) of the two hybrid controllers used for the two different science data-taking operational modes was compared with the performance achieved using an all-thruster controller design [7]. The strengths and weaknesses of the Cassini hybrid control architecture(s) were assessed quantitatively.

VII. DAWN HYBRID CONTROL WORKSHOP REPORT

At the workshop, a representative from OSC presented a summary-level talk on the Dawn hybrid control approach and its status. OSC is the Dawn prime spacecraft contractor. Dawn, a low-thrust interplanetary spacecraft (see Fig. 5) was launched in September 2007 and is the ninth Discovery mission in NASA's SMD. The program is managed and the spacecraft is operated by JPL. In June of 2010, during its cruise to the asteroid Vesta, the first of its two asteroid destinations, the spacecraft experienced a high friction anomaly on one of its four RWs, namely RW-4. This anomalous RW was taken out of the attitude control loop and some limited testing indicated that it was likely unusable for the approaching Vesta campaign. To preserve the remaining three wheels for science operations at the asteroids, the backup RCS thrusters were activated for attitude control for the remainder of the cruise to Vesta. Simultaneously, as a contingency against an additional RW failure in the remaining, now non-redundant, three-wheel complement, an effort was initiated in September 2010 to develop a hybrid control mode that would use only two RWs in a mixed-actuator mode together with thrusters to provide full three-axis attitude control. Compared to the existing backup all-thruster controller, this mixed-actuator hybrid control mode was designed to provide better pointing with less propellant expenditure during science operations.



Fig. 5: Dawn Spacecraft

At the workshop, OSC mentioned that another motivation for the development was the recognition that the root cause of the RW anomaly was not entirely understood, and therefore it was not possible to mitigate the risk solely by imposing new operational guidelines/constraints on the remaining RWs, as had been done on other missions. The hybrid mode needed to have the capability of performing all planned science operations with activation at any time during the mission. It also needed to be designed, implemented, and tested rather quickly, since it required a new version of the flight software that had to be loaded onto the spacecraft well before the beginning of science operations at the asteroid Vesta.

Hybrid attitude controller design challenges for Dawn included the requirement to maintain nominal science payload pointing, especially with the relatively large attitude rates required in the low altitude orbits, but also the requirement for maintaining a communications link to Earth with the High Gain Antenna (HGA). The latter requires relatively tight pointing (i.e., less than a degree) on the two axes normal to the HGA's boresight. It was understood that level of pointing might not be possible with only two RWs depending on the orientation of their torque axes.

As described above, a hybrid mixed-actuator attitude controller using RWs together with electromagnetic torque rods had been developed for NASA's FUSE spacecraft, one of OSC's earlier LEO spacecraft that also experienced problems with its wheels and this concept was carried forward to the Dawn hybrid controller. A similar implementation was developed for NASA's TIMED spacecraft, which as described above, is another LEO spacecraft using electromagnetic torque rods. Using high-torque thrusters instead of low-torque magnetic control imposed its own set of design challenges, particularly in the need for a low-bandwidth thruster control loop that would minimize thruster pulsing and propellant consumption while still providing acceptable pointing. The thruster control loop was also designed to minimize its coupling into the wheel control loops. The major implementation challenge was to keep changes to the existing flight software to a minimum, both to reduce testing and verification time and to avoid large-scale changes to mission operations procedures, which would impose a risk given the short time to the beginning of the Vesta campaign. Thus, a surgical approach to the flight software implementation was adopted, whereby all changes would be decoupled from the existing software to the maximum extent possible and would have no effect on normal, i.e., non-mixed mode, operations. After relatively short development, implementation, and testing phases, the new version of the flight software containing the hybrid controller was uploaded to the spacecraft in April 2011, providing risk mitigation and additional mission flexibility. Dawn arrived at Vesta in May 2011 after a flyby of Mars in February 2009. Vesta science operations were performed entirely on three wheels: RW-1, RW-2, and RW-3. After a yearlong successful science campaign at Vesta, Dawn departed for its next destination, the asteroid Ceres, with an arrival date there planned for in early 2015. In August 2012, RW-3 experienced a high-friction anomaly and Dawn's attitude control was again transitioned to an all thruster mode to preserve life on the remaining two functional wheels. At the workshop, it was stated that the spacecraft would remain in an all-thruster control mode until reaching Ceres and that inflight tests of the Dawn hybrid controller were planned for later in 2013.

Also at the workshop, OSC described how the 2-RW hybrid controller was designed, developed, and implemented on the Dawn spacecraft to provide mission flexibility for the contingency of multiple failures of the primary RW actuators. Although the pointing performance is less than that achievable with the nominal all-wheel control scheme, it is still sufficient to meet the Dawn science objectives. Since it is a more propellant-

efficient mode than the backup all-thruster control, reducing the rate of consumption of a limited resource, it allows for a longer duration of the remaining mission. The hybrid controller was implemented well into the Dawn mission, retrofitted into the flight software with one of the constraints being to make it as transparent as possible to normal operations. The OSC representative described some of the operational considerations for preparing Dawn to use a hybrid actuator configuration.

References 8 and 9 provide the details of the Dawn hybrid control experiences. In particular, Reference 9 provides a Dawn hybrid control operations update with recent inflight test performance results included.

VIII. MARS ODYSSEY HYBRID CONTROL WORKSHOP REPORT

The Mars Odyssey spacecraft, launched on 7 April 2001, is an orbiter carrying science experiments designed to make global observations of Mars to improve our understanding of the planet's climate and geologic history, including the search for water and evidence of life-sustaining environments. LMC built and operates the Odyssey Mars Orbiter under contract to NASA, JPL. The vehicle has been in orbit around Mars now for well over a decade and in December 2010, it became the longest-lived vehicle orbiting Mars. In addition to its science mission, Odyssey's other mission is to provide communication relay for NASA's vehicles on the Martian surface. Fig. 6 depicts the general configuration of the Odyssey spacecraft in its nominal nadir-pointing orientation. The primary attitude control actuators are three RWs each aligned with the three vehicle coordinate frame axes, and a nominally inactive fourth "skew" RW to be employed in case of failure of any one other RW. Note the relatively long gamma ray spectrometer boom, in addition to its single-wing solar array, yields non-symmetric inertial properties for the Odyssey vehicle. This causes non-negligible gravity gradient disturbance torques.

On 8 June 2012, the RW-1 (i.e., the x-axis wheel) experienced a stiction anomaly causing the Mars Odyssey spacecraft to enter a safe mode [10]. An increase in wheel bearing friction prevented RW-1 from producing the control torque commanded by the spacecraft's ACS, which in turn allowed an attitude error to grow and exceed the safe mode entry limit. Recovery from this safe hold necessitated activation of the skew RW. It was stated at the workshop that there was no plan to attempt to use the failed RW-1 unless another RW failure occurs.

Shortly thereafter, NASA directed JPL and LMC to initiate development of a contingency thruster-only (all thruster) controller and a contingency 2-RW hybrid controller (with thrusters for accomplishing control on one axis) to maintain three-axis control of the spacecraft in the event of a second wheel anomaly/failure. These contingency modes of operation would be required to accomplish both the nominal nadir pointing and maneuver/inertially hold the spacecraft to point its HGA properly towards Earth for data downlink communication periods once or twice a day.

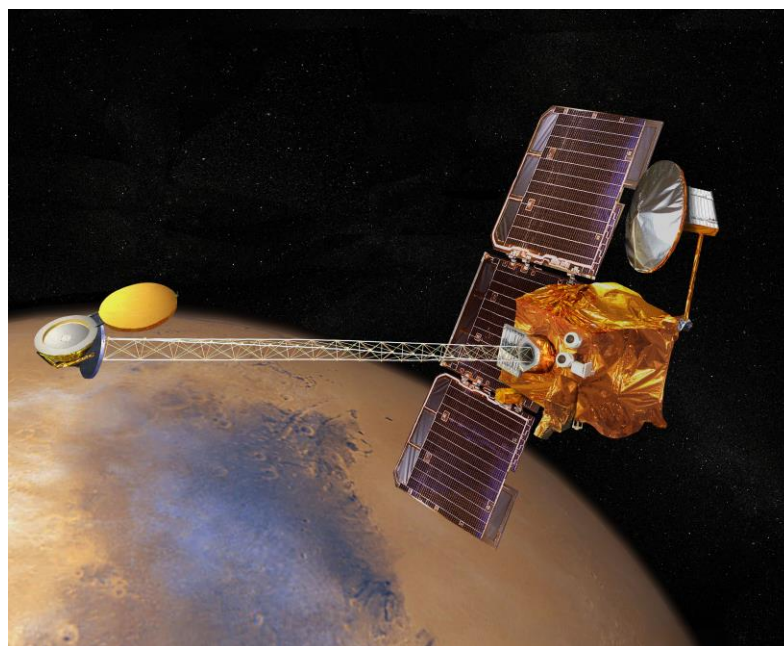


Fig. 6: Mars Odyssey Spacecraft

LMC designed a 2-RW hybrid ACS which used various combinations of functional wheel pairs (e.g., the RW-2 and the skew wheel pair, the RW-3 and the skew wheel pair, and RW-2 and RW-3 pair) to control two of the spacecraft's axes and used thrusters to provide control torques for the third axis [11]. A rotated control reference frame, called the reaction wheel control plane (RCP), was employed such that the axis controlled by the thrusters is orthogonal to the wheels. A very positive implementation aspect was that the Odyssey hybrid controller could be implemented with only ACS data parameter changes, so patching of existing ACS flight software would not be required. According to the LMC workshop presenter, this was primarily due to the simplicity and elegance of the baseline attitude controller architecture.

Another positive attribute of the Mars Odyssey baseline ACS architecture came into play when the LMC team was addressing a problem that emerged once the spacecraft began to operate on the skew wheel following the failure of RW-1. Initially it was not possible to cleanly desaturate the skew wheel's x-axis momentum component because of the coupling into the spacecraft's y-axis and z-axis. Hence, a study had been initiated by JPL aimed at determining ACS "algorithm changes" that would allow for x-axis momentum desaturations. After analyzing the ACS architecture, it was observed that a simple change to the contents of a single on-board ACS parameter matrix would allow the skew wheel to be desaturated without affecting the other vehicle axes. Therefore, no ACS flight-software algorithm changes were required, which is just another result of the flexibility built into this particular ACS design.

However, there were some 2-RW hybrid control issues that emerged from the preliminary analyses and simulations of flying in the nominal nadir-pointing attitude. The momentum stored in each wheel typically cycles up and down as the spacecraft orbits Mars. If one of those axes is controlled by thrusters, that wheel's momentum cannot cycle up and down, and it is taken out immediately. There were concerns about sensitivity to thruster variations or impingement. In addition, it was observed that precessional torque (from 'dragging' the RW angular momentum vector around) induced additional thruster firings.

The relative performance, in terms of propellant consumption, of the various possible contingency control modes and actuator hardware configurations were performed. In particular, the performance of the two-wheel controller was compared to the Thruster Only controller. Attempts were made to optimize the vehicle's pitch angle to minimize the gravity gradient disturbance torque disturbance. In addition, the hybrid control designers at LMC cleverly chose an attitude that aligned the RCP with the spacecraft's orbit plane to eliminate the undesirable RW momentum vector precessional torques and to improve propellant efficiency.

Simulation results indicated that the thruster-controlled axis would be inefficient due to the thruster configuration so hybrid control could actually be worse, in the sense of more propellant consumption, than the thruster-only attitude control mode. At the time of the workshop, it appeared that there was not much improvement to be gained via the 2-RW hybrid-control mode over the thruster-only mode at least for the nominal nadir-pointing portion of the mission. The team understood that a propellant-efficient, three-axis thruster-only contingency attitude control mode, using a one-sided deadbanding approach, would eliminate the need for or any advantage of a 2-RW hybrid mode.

As mentioned earlier, the hybrid attitude controller would be required to maneuver the spacecraft to the proper attitude for HGA communication with Earth and inertially hold that attitude for the duration of that data downlink period. Initial simulation results showed significant propellant was consumed during the HGA maneuver and inertial hold portion of the mission, when using both the thruster-only and the 2-RW hybrid controllers. The LMC engineers were subsequently able to develop an improved, more propellant-efficient, two-segment approach for maneuvering the spacecraft to the HGA communication attitude. At the time of the workshop, there were indications that the greatest potential benefit was to be gained with hybrid slews to the HGA communication attitude. Further investigation of operational optimization was planned, for example, re-considering the number of and the specific scheduling of the maneuvers for HGA-Earth communications.

Also further tuning of and comparison of the 2-RW and thruster-only control modes is planned with particular attention to propellant consumption and operational complexity. One of the Odyssey team's conclusions expressed at the workshop was that orbiting, non-symmetrical spacecraft make for non-optimal hybrid control due to a combination of precessional torques and gravity gradient torques. Lastly, it was expressed that further efficiency optimization of both 2-RW hybrid control and thruster only (all thruster) was probable. As it currently stands, if another RW fails on the Mars Odyssey spacecraft, it will revert to the thruster-only (all thruster) contingency three-axis attitude control mode versus a 2-RW plus thrusters hybrid control mode of attitude control.

IX. KEPLER WORKSHOP REPORT

The Kepler mission (NASA Discovery Mission #10) was specifically formulated to survey a portion of our region of the Milky Way galaxy to discover dozens of Earth-size planets in or near the habitable zone and determine how many of the billions of stars in our galaxy have such planets. It is NASA's first mission capable of finding Earth-size planets around other stars. The Kepler spacecraft (see Fig. 7), which flies in a heliocentric Earth-trailing mission orbit, was launched March 7, 2009 and completed its 3.5-year prime mission in November 2012.

The Kepler spacecraft, which was designed and built by Ball Aerospace and Technologies Corporation (BATC) of Boulder, Colorado, nominally employs a set of four (4) RW actuators to generate attitude control torques to slew, point, and precisely stabilize the vehicle [12]. A minimum of three RWs is required to provide the zero-momentum, three-axis stabilization of the spacecraft. Kepler employs RWs very similar to the ones flown on the TIMED mission described earlier. It was mentioned at the workshop that the TIMED RW failure occurred during the build of the Kepler RWs and it was decided by the project to rework the Kepler wheels prior to launch.

While there was not any significant discussion on Kepler hybrid attitude control system design efforts at the workshop, the prevailing viewpoint at the time was that this mission would greatly benefit from proactively developing a two-wheel hybrid controller as a protection from another wheel failure. The BATC representative at the workshop did describe the way in which the Kepler RW-2 performed anomalously for a period of time and then eventually failed [13]. In July 2012, Kepler's RW-2 friction increased beyond the control law's torque command; analysis showed friction torque of approximately 140 mN-m, up from a nominal friction torque of 20 mN-m. Following that RW-2 anomaly, Kepler had continued performing normal mission pointing on the remaining three RWs with the following mitigations: increased RW heater setpoint increased minimum speed to ensure an all ElastoHydroDynamic (EHD) bearing operating regime, bi-directional wheel spin operation, and implementation of a very propellant-efficient thruster-controlled safe mode.

It should be noted that at the time of the workshop, BATC had not yet initiated work on the design of a 2-RW hybrid attitude controller. At that time (i.e., April 2013), BATC was primarily focused on managing the remaining three wheels, as described above, in order to preserve their remaining life. However, JPL had conducted a high-level assessment of a 2-RW (plus thrusters) hybrid attitude controller for the Kepler spacecraft. Therefore, at the workshop, results were presented by a JPL representative summarizing their preliminary technical feasibility investigation [14]. These results indicated that capability of achieving the Kepler mission's original long-term pointing stability of 9 milliarcseconds while staring at the original Cygnus science target field-of-view would not be feasible with a two-wheel (plus thrusters) hybrid controller. This was primarily because the minimum impulse bit of the spacecraft's propulsion subsystem thrusters was not originally sized for fine attitude control purposes.

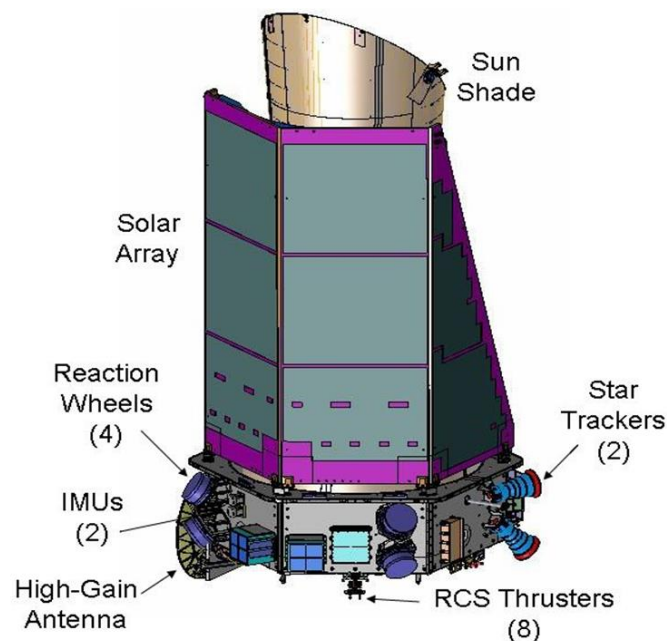


Fig. 7: Kepler Spacecraft

X. HYBRID ATTITUDE CONTROL LESSONS LEARNED FROM WORKSHOP

There were several key lessons learned that emerged from the NASA Spacecraft Hybrid Attitude Control Workshop, including the following:

- To avoid limitations on the available contingency hybrid control design space, and to achieve potential improvements for future mission applications, ACS designers should consider designing in provisions for the hybrid mode during the normal spacecraft development cycle.
- The creation of a new hybrid control frame (reference frame) to permit decomposition of the RW control torques from the thruster/MTB (alternate actuator) control torques, appears to be a good basic first step in designing a new hybrid controller.
- Hybrid control system designers should consider plotting/reporting ACS simulation results in the coordinate frame containing all the control torque from the remaining two RWs (e.g., the TIMED “Pseudo Frame”), rather than normal spacecraft body frame, to provide insights for the hybrid controller tuning process.
- When able to implement it, consider the flight-proven practice, as resurrected from the 1960s, of establishing a momentum bias on the vehicle with the remaining two reaction wheels to provide a gyroscopic restraint about two of the spacecraft axes.
- There is an ACS architectural lesson learned from the TIMED hybrid control experience concerning RW control torque distribution. In the early stages of the ACS design process, the analysts should consider the control torque distribution in the spacecraft body frame for all possible 2-RW combinations.
- Analysts should consider ways that wheel orientations should be optimized to balance the remaining 2-RW control torque across all three spacecraft body axes.
- There may be advantages in having the 4th RW be articulable, as was done on Cassini.
- Thruster firings in hybrid attitude control mode or all-thruster-control mode can cause unwanted spacecraft Delta-V, which could complicate the mission spaceflight navigation process.
- There appears to be limited need for the development of new, or the enhancement of existing, analytical (modeling and simulation) tools for hybrid controller design/analysis. Existing ACS design and analysis tools appear to be satisfactory.
- Performing large-angle spacecraft attitude slew maneuvers (for communications or power purposes) appears to be a common stressing challenge for 2-RW hybrid attitude control.
- When developing a hybrid attitude control scheme for extended mission operations one should consider and analytically investigate different spacecraft attitude orientations for the follow-on mission that can exploit local environmental torques to provide control rather than disturbances.
- There is a critical need for and great benefits of having spare ACS flight software table elements, telemetry elements, and commands. All the spare flight software, table elements, telemetry words, and commands that had been added to the ACS flight software in an early build were used by the time OSC completed implementation of their new hybrid control ACS algorithms for the FUSE spacecraft. Having these spares available made quick flight software patches safer and much easier.
- There is critical need/benefit in maintaining the spacecraft’s ACS Engineering Development Units in a FlatSat laboratory testbed environment. Connecting this ACS testbed to the spacecraft’s ground system will permit high-fidelity verification testing of the new hybrid control commands, telemetry, operational scripts, and operational procedures and will also allow the flight operations team to train on the modified ACS.

Finally, there was a general observation that emerged during the workshop discussions regarding ACS operations for long-extended missions. For missions with significantly extended flight operations (well beyond the prime mission duration), it is particularly important for the flight operations team to identify, track/monitor, and carefully manage all on-board flight software clocks, timers, counters, and other similar functions that ‘rollover’ at some point in time.

XI. POST-WORKSHOP HYBRID ATTITUDE CONTROL INITIATIVES

Although there was progress on hybrid control on other NASA missions (for example, inflight testing of the Dawn hybrid controller has recently been performed by JPL and OSC), the majority of the post-workshop activity has been focused on identifying and developing a technically feasible, well-performing, operational simple and easily implementable two-wheel hybrid controller for the Kepler spacecraft. Design of a viable Kepler two-wheel hybrid controller was greatly spurred on by the fact that shortly after the April 2013 workshop, a second Kepler RW, that being RW-4, performed anomalously and subsequently failed.

By the end of April 2013, all appropriate mitigation steps to prolong the life of Kepler's RW-4 had been taken. Unfortunately, the wheel life extension operational mitigations described above were not sufficient to protect Kepler's RW-4, which had exhibited symptoms of increasing bearing friction. At the routine communications contact on 14 May 2013, the Kepler spacecraft was unexpectedly discovered by its flight operations team to be in its Thruster-Controlled Safe Mode. In this safe mode, the vehicle was in a power-positive/thermally benign orientation with the solar panels facing the Sun, slowly spinning about the Sun-line. A RW anomaly review team concurred that the telemetry data appeared to unambiguously indicate that RW-4 failed on 11 May 2013. The Kepler Project Office at NASA's Ames Research Center (ARC) and the prime spacecraft contractor (BATC) then turned their collective attention to preserving the remaining propellant, attempting to return the failed wheels to service at reduced performance levels, and investigating attitude control techniques for collecting scientifically meaningful data using the combination of the two remaining functional wheels and thrusters.

As a proactive follow-up activity initiated shortly after the April 2013 workshop, controls engineers at NASA's Goddard Space Flight Center (GSFC) designed, modeled, and simulated a momentum-bias approach for accomplishing three-axis attitude control using only two RWs and no thrusters. The work described in Reference 15, was undertaken under direction and sponsorship of the NESC. It is an independent exploration of the feasibility of two-wheel attitude control on a Kepler-class spacecraft and the constraints that inevitably arise, which considers the bounding problem: *Can spacecraft attitude be maintained indefinitely using only two RWs in the presence of solar radiation pressure torque?* Since no thruster usage is a baseline assumption in this work, the two RWs are responsible for not only three-axis attitude control, but also angular momentum management. The intent of this work was not to propose yet another candidate control architecture, but rather to understand the conditions that any such architecture must satisfy to be a viable solution. Two complementary algorithms for inertially pointing a representative, but Kepler-like, spacecraft using the wheels only are discussed in Reference 15. The benefits of using a momentum bias are described and that paper serves to quantify and document some of the fundamental hybrid control constraints and limitations.

Shortly following the failure of RW-4 ACS engineers at BATC designed a new two-wheel/thruster hybrid controller for the repurposed Kepler spacecraft. Reference 16 discusses the BATC hybrid control architecture that uses momentum biasing of the two remaining wheels and low duty cycle use of the RCS thrusters to provide 3-axis control. It also discusses general guidelines for operating the vehicle in this mode.

Because the pointing stability of 9 milliarcsecond required for the primary Kepler mission appears to not be achievable with only two RWs, after the failure of Kepler's second RW in August 2013, the Kepler project scientist at NASA ARC issued an open call for science white papers seeking ideas to repurpose a mission for the Kepler observatory. The NESC has supported the Kepler Project Office in the process of identifying hybrid control/science observation combinations for a potential repurposed Kepler spacecraft. NESC engineers provided technical support to define attributes, preliminary performance estimates, and flight implementation challenges of the selected baseline hybrid control concept. In conjunction with the science white paper call, the NESC released, through NASA's Langley Research Center, a NASA Request For Information (RFI) seeking new hybrid control concepts and innovative hybrid control approaches for possible application to the distressed Kepler spacecraft. The most desired alternate science operations would involve long-term pointing with as much pointing stability as possible. Therefore, the challenge was to develop a 2-RW hybrid mode that could deliver this type of operation and performance while pointed at some other science target(s).

Numerous science ideas and several concepts relevant to two-wheel hybrid control were surfaced through the combination of the science white paper call and the NASA RFI. The NESC reviewed and evaluated all the RFI responses received based on: 1) their relevance to the Kepler hybrid control problem, 2) their likelihood of technical implementation success, and 3) their degree of operational difficulty. The NESC also planned and conducted (in September 2013) a 2-day Kepler Pointing Technical Interface Meeting with the Kepler Project Office engineering and science teams at NASA ARC to help them identify the best hybrid attitude control approach for a repurposed Kepler spacecraft. Not surprisingly, given their in-depth knowledge of the spacecraft and its operating environment, the BATC-developed 2-RW hybrid control architecture has been adopted by the Project Office as the baseline approach for the repurposed Kepler mission [16].

The Kepler Project Office at ARC has proposed to the NASA SMD a repurposed Kepler mission called K2. The Kepler science, engineering, and flight operations teams believe this new K2 mission is technically feasible and operationally straightforward with the two remaining wheels. K2 apparently has the potential to discover many hundreds of new, small exoplanets around low-mass stars located in or near the ecliptic plane. Therefore, the key new operational and science observation constraint here is limiting the K2 science observations to science targets in or near the ecliptic plane where the solar radiation pressure (SRP) disturbance torques can be carefully

balanced to minimize boresight roll. Initially, there was concern that this approach would be similar to balancing on a knife edge but data from some early inflight K2 testing shows the SRP disturbance torque profile to be more benign (i.e., not so steep) as originally suspected. However, more inflight testing will be needed to confirm this. The attitude control engineers at BATC have done enough ACS analysis [16], and the results of the several early ecliptic-plane K2 performance tests are favorable enough to demonstrate the feasibility of this hybrid control scheme. Additionally, these tests have allowed the Kepler scientists to develop initial predictions of K2 photometric performance. Trade studies are planned to assess the number of targets, cadence durations, initial fields of view, and observing strategies. If the Kepler Project's proposal is approved, it is very likely that K2 will observe many different target fields during a sequence of 2-month to 3-month campaigns over the next few years.

It is worth noting that two of the lessons learned that emerged from the NASA Spacecraft Hybrid Attitude Control Workshop came very much into play in the design of the K2 ACS by BATC. The BATC K2 ACS design will employ a momentum bias about the spacecraft z-axis. That momentum bias will be oriented normal to the Kepler spacecraft's orbit plane such that inertial targets in that plane can be tracked simply by modulating the bias. Kepler is unusual because of its tight roll pointing stability requirement; most science telescopes would most likely have the momentum bias along their optical boresight axis rather than perpendicular to it as will be done on K2. Secondly, it should be noted that K2 will be pointed in the ecliptic plane in order to exploit the SRP disturbance torque rather than to fight it. This followed serendipitously from the best engineering practice of using the momentum bias mentioned above. These two concepts were suggested to BATC by NESC in support of their hybrid controller design work to enable Kepler repurposing.

In parallel with all this activity focused on the repurposed Kepler spacecraft research into ways to control under-actuated vehicles is currently on going at the Naval Postgraduate School (NPS) under NESC sponsorship. The topic of how to control under-actuated vehicles has been studied before [17]. The researchers at the NPS are challenging the convention wisdom on spacecraft attitude control that says three independent controllers are needed for precision pointing. This wisdom not only is intuitively well founded as three controllers span a three-dimensional space but also the concept is in agreement with fundamental mathematical theory on linear controllability. NPS maintains that nonlinear controllability (without linearization) is not only practical but it also defies intuition: a linearized system may be controllable but really be uncontrollable due to nonlinear (i.e., practical) effects. Additionally, and more importantly to the case of under-actuated spacecraft control of primary interest here, a nonlinear system may be controllable but the linearized system may be uncontrollable. Thus, it is possible to get false positives and negatives on practical controllability using a linear analysis.

In Reference 18, the NPS researchers address nonlinear, and hence, practical controllability without linearization using a combination of well-known and recent results in mathematical system theory. In particular, they consider the particular problem of nonlinear controllability of a spacecraft equipped with just two RWs.

The application of these mathematical results to Kepler is still ongoing at NPS. Should the positive preliminary results stand up to more in-depth investigation, this approach has the potential to offer a new solution path to possibly recovering the capability to perform the original Kepler mission. However, much more work remains to be done before this can be definitively determined.

XII. SOME FUTURE CONSIDERATIONS FOR HYBRID ATTITUDE CONTROL

Beyond the lessons learned mentioned above that emerged from the workshop, there are several associated technical areas that appear promising and which should be considered for future hybrid attitude control applications, such as, but not limited to the following:

- Simple and flexible spacecraft ACS architectures that permit substitution of hybrid actuators without flight software code modifications
- Nonlinear control laws
- Nonlinear optimization solvers
- Techniques for implementing computationally efficient on-board real-time nonlinear control laws/nonlinear optimization solvers on typical spacecraft flight processors
- Improved high-fidelity disturbance torque modeling, particularly the SRP disturbance
- Simple and reliable articulation platforms for re-positioning RWs
- Ultra-low minimum impulse bit micro-propulsion (cold gas) vernier attitude control thrusters as potential substitutes for RW
- Linear proportional high-efficiency magnetic torquers

XIII. CONCLUSION

This paper describes the highlights of the first NASA Spacecraft Hybrid Attitude Control Workshop that was held in Greenbelt, Maryland in April of 2013. In support of risk/benefit assessments for Kepler, Dawn, Mars Odyssey, and other science spacecraft flight operations, the workshop gathered, captured, and disseminated GN&C engineering knowledge and lessons learned regarding contingency spacecraft attitude control techniques using only two RWs. The fundamental driver for holding this workshop was to help inform and prepare the Kepler, Dawn, and Mars Odyssey ACS teams for understanding better the technical challenges, risks, and benefits of potential 2-RW hybrid attitude control mode operations on their spacecraft.

Given its heightened interest in the design, development, and flight implementation of mixed-actuator hybrid attitude control for science spacecraft, NASA will likely be further studying past relevant experiences and evaluating new techniques for controlling spacecraft that have less than three functional RWs. This interest is driven by a number of recent RWs failures on aging, but still scientifically productive, NASA spacecraft and is motivated to ensure continued longevity of NASA's scientific spacecraft fleet well past their prime mission lifetimes.

The detailed results of the first NASA Spacecraft Hybrid Attitude Control Workshop have been documented in an NESC engineering final report [19]. It is quite likely that the NESC will sponsor a second NASA Spacecraft Hybrid Attitude Control Workshop to be held in the coming year.

Some relevant recent hybrid control activities were described with an emphasis on work done in support of a repurposed Kepler spacecraft. Specific technical areas for future considerations regarding spacecraft hybrid attitude control were also identified in this paper.

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